10.18 HORIZONTAL AND VERTICAL DISTRIBUTION OF OZONE IN THE HOUSTON AREA DURING THE 8/29 - 9/6/2000 POLLUTION EPISODE

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1. INTRODUCTION

The nine-day period from August 29th through September 6th 2000 represented the longest consecutive string of ozone exceedance days (1-hour surface ozone concentrations greater than 125 ppbv) in the Houston, TX area during the 2000 ozone season. The peak ozone concentrations measured during this period exceeded 200 ppbv. This ozone pollution episode occurred in the middle of the month-long Texas Air Quality Study (TexAQS 2000), which was aimed at identifying the chemical and meteorological processes that cause these kinds of extreme ozone events in the Houston area. More information on the objectives of the TexAQS 2000 study and preliminary results can be found at http://www.utexas.edu/research/ceer/texaqs/.

The first three days (August 29th - 31st) of the high-ozone pollution episode were characterized by very light-wind conditions during the middle of the day and an off- to onshore flow reversal in the afternoon, whereas during the remaining six days (September 1st - 6th) the wind was blowing steadily from westerly or easterly directions all day. In this paper we examine the effect of these different flow conditions on the three-dimensional distribution of ozone, ozone peak values, and transport patterns.

2. INSTRUMENTATION

During TexAQS 2000, a large array of instruments, both ground-based and airborne, was deployed to characterize the atmospheric chemical composition and the meteorological conditions in the greater Houston area. The results shown in this paper are primarily based on data gathered with the airborne ozone and aerosol lidar of the National Oceanic and Atmospheric Administration (NOAA) / Environmental Technology Laboratory (ETL). The airborne lidar's role during TexAQS 2000 was to document the horizontal and vertical distribution of ozone and aerosol in the Houston area. The lidar was flown onboard a DC-3 cargo aircraft, usually at an altitude of about 3500 m above ground level (AGL). The nadir-looking lidar measured vertical profiles of ozone concentration and aerosol backscatter between approximately 2500 m AGL and the surface. The time resolution of these measurements was 10 s (corresponding to a 600-m horizontal resolution) and the vertical resolution was 90 m for ozone and 15 m for aerosol backscatter. Details about the lidar instrument and information about the ozone and aerosol retrieval methods can be found in Alvarez II et al. (1998). Banta et al. (1998) and Senff et al. (1998) reported on applications of the ETL airborne lidar in previous air quality studies.

Part of the instrument array at TexAQS 2000 was a network of five wind profilers that provided, on a continuous basis, hourly averages of wind speed and direction measurements in the lower troposphere. We used back trajectories calculated from the wind profiler network data to gain an understanding of the origin and transport patterns of the ozone plumes that were detected with the airborne ozone lidar.

The National Center for Atmospheric Research (NCAR) Electra aircraft was one of the heavily instrumented research aircraft flown during TexAQS 2000 to study the chemical composition of the atmosphere over the Houston area. We incorporated chemistry measurements made onboard the Electra aircraft into our analysis, both to compare the in situ ozone measurements with the remotely sensed lidar data and to characterize the chemical makeup of the ozone plumes identified by the airborne lidar.

3. MEASUREMENTS

During August 29th - 31st, very high ozone concentrations and widespread ozone exceedances registered by the Houston Regional Monitoring (HRM) network occurred in the Houston area. During the later part of the pollution episode, when well-defined flow conditions prevailed (September 1st - 6th), peak ozone values in the Houston vicinity were lower and exceedances were not as widespread compared to the previous three days. To demonstrate how the different flow regimes encountered during the August 29th - September 6th pollution episode affected the distribution and peak concentrations of ozone in the Houston area we show results for 2 days: August 29th, as an example for the ozone distribution found under light-wind conditions followed by an off- to onshore flow reversal, and September 6th, as an example for the ozone distribution encountered under well-defined flow conditions.

3.1 *August 29th*

On August 29th, as well as on August 30th and August 31st, very high ozone concentrations were measured in the Houston area, especially near the western and

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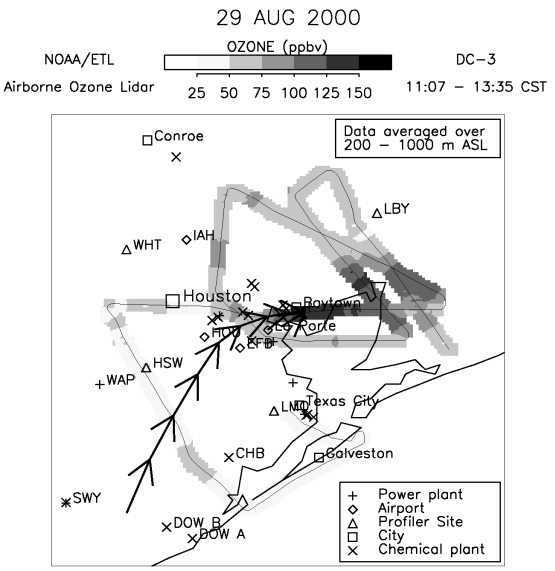

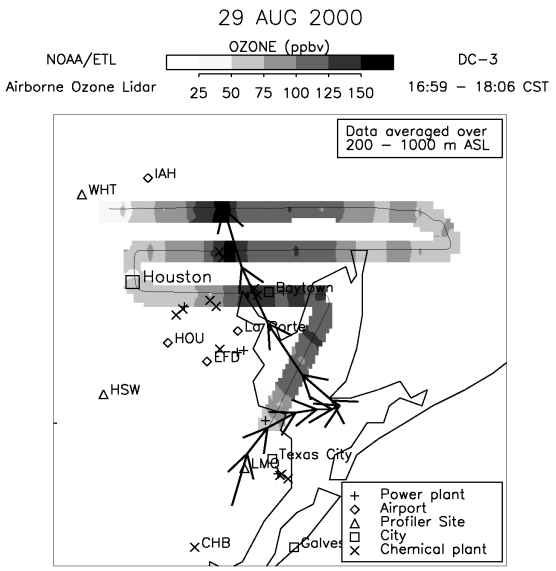

***Figure 1**: Horizontal distribution of ozone as measured with NOAA/ETL's airborne lidar along the DC-3 flight path on August 29th between 11:07 and 13:35 CST. Ozone concentrations are vertically averaged between 200 and 1000 m ASL. The sequence of arrows represents a back trajectory calculated from the wind profiler network data. Locations of the five wind profilers are indicated by triangles.*

***Figure 2**: Same as in Fig. 1 except data are form a flight leg flown on August 29th between 16:59 and 18:06 CST.*

northern shores of Galveston Bay (see Figs. 1 and 2). All three days were characterized by a morning westerly offshore flow followed by a period of stagnating winds around midday, and a reversal to a southeasterly onshore flow with the onset of the sea breeze in the afternoon. The meteorological conditions on these three days were very similar, but subtle differences in the flow pattern, the timing of the sea breeze onset, and different mixed layer depths caused significant discrepancies in ozone distribution and ozone peak values. Even though peak ozone values were higher on the other two days, we chose to show data from August 29th because the flow reversal associated with the afternoon sea breeze and its impact on the ozone distribution was very pronounced on that day. For an in-depth discussion of the impact of the flow reversal on ozone distribution on August 30th see Banta et al. (2002).

Figure 1 shows the horizontal distribution of ozone around midday on August 29th measured by the airborne lidar along the DC-3 flight track and overlaid on a map of the Houston area. The ozone concentrations shown in Fig. 1 were produced by averaging the range-resolved ozone profiles between 200 m and 1000 m above sea level (ASL). The highest ozone concentrations, approaching 150 ppbv, were found near the northern shore of Galveston Bay. Also plotted in Fig. 1, as a sequence of arrows, is a back trajectory. The trajectory was calculated from wind profiler measurements that were averaged over the same altitude range as the lidar data. Each arrow represents the path an air parcel traveled in one hour. The start time of the back trajectory calculation is the time when the lidar flew over the start location of the trajectory, in this case around noon CST. The back trajectory reveals that the high ozone concentrations just north of Galveston Bay were associated with emissions from the Houston Ship Channel area. The Ship Channel is a waterway connecting Houston Harbor and Galveston Bay, along which a large number of refineries and petrochemical plants is located.

Figure 2 depicts the ozone distribution measured by the airborne lidar in the Houston area in the late afternoon of August 29th. The largest amounts of ozone were found in a swath extending from the middle of Galveston Bay northwestward to the east side of the Houston metropolitan area. Peak concentrations in the center of this ozone plume exceeded 150 ppbv. The back trajectory indicates that this plume of ozone was associated with emissions from industrial sources near Texas City, another agglomerate of petrochemical plants. In the morning, the emissions of these sources were carried offshore over Galveston Bay, where they lingered as the winds became light during the middle of the day (indicated by the short trajectory arrows). In the early afternoon, with the onset of the sea breeze, the wind direction switched from west to southeast and the flow accelerated. The sea breeze carried the aged, Texas City pollution plume across Galveston Bay and over the source regions at the eastern end of the Ship Channel, thus increasing the already high ozone concentrations in this area that had accumulated during the middle of the day.

3.2 *September 6th*

During the September 1st - 6th portion of the high-ozone episode, the winds blew steadily from westerly or easterly directions, which caused the pollution plumes from the Houston urban, Ship Channel, and Texas City areas to be transported away from the source regions. Of the airborne lidar data collected during this period, the measurements on September 6th provide the most striking example of how pollution originating in urban and industrial areas of the Houston metroplex can impact air quality in the surrounding, mostly source-free areas.

Figure 3 shows the ozone distribution measured by the lidar on September 6th between late morning and mid-afternoon. On that day, the DC-3 aircraft flew two flight legs upwind and 10 flight legs downwind of the Houston metropolitan area. The flight legs were spaced apart by about 20 km. The wind was blowing steadily all day from a northeasterly direction at speeds of 5 to 10 m/s. A well-defined plume of ozone originating in the Houston urban/Ship Channel area and extending to about 200 km southwest of the urban area showed up prominently in the lidar data. Ozone concentrations in the core of the plume exceeded 130 ppbv to a downwind distance of about 150 km, with higher values measured closer to the Houston metropolitan area. A second, although weaker ozone plume, originating in the Texas City area and extending to Bay City can be identified in Fig. 3. Peak ozone values in that plume reached about 120 ppbv.

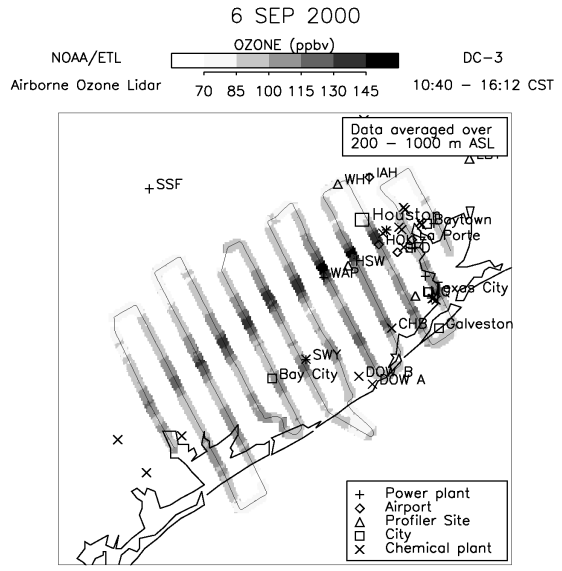

***Figure 3**: Horizontal distribution of vertically averaged ozone measured with the airborne lidar on September 6th between 10:40 and 16:12 CST. Note the different grey scale for ozone concentration as compared to Figs. 1 and 2.*

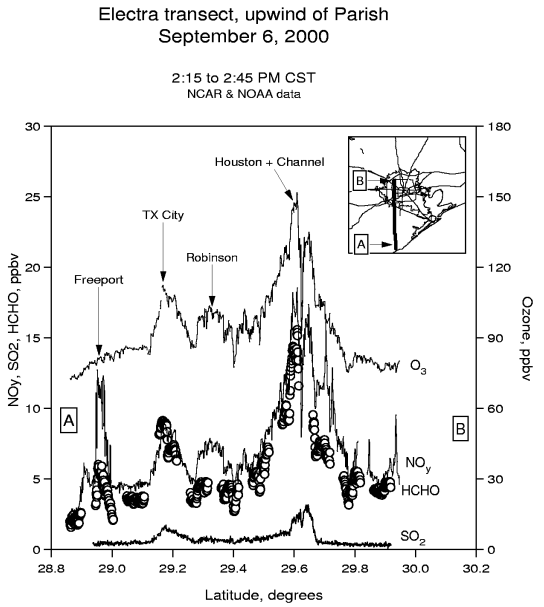

***Figure 4**: Traces of O_3, NO_y, SO_2, and formaldehyde measured with in situ sensors on board the Electra aircraft on the afternoon of September 6th during a flight transect downwind of the Houston urban area. Location of the flight leg is indicated in the inset figure. The flight altitude of the Electra was 650 m ASL.*

The NCAR Electra aircraft with its comprehensive suite of in situ chemistry sensors also flew multiple transects downwind of the Houston area on September 6th. Figure 4 shows traces of O_3, NO_y, SO_2, and formaldehyde that were recorded by instruments onboard the Electra during a transect that nearly paralleled the DC-3 lidar aircraft transect starting at the DOW Chemical plants (DOW A and DOW B in Fig. 3) and extending northwestward passing just east of the W. A. Parish power plant (WAP in Fig. 3). The in situ chemistry measurements in Fig. 4 were recorded at a flight altitude of 650 m ASL between 14:15 and 14:45 CST, about 2 hours after the airborne lidar had flown over this area. The Houston urban/Ship Channel and Texas City pollution plumes are clearly identified by the peaks in O_3, NO_y, and SO_2 concentrations. The ozone values measured by the Electra in situ sensors agree well with the ozone concentrations measured by the airborne lidar. The high correlation between O_3 and formaldehyde in the Houston urban/Ship Channel and Texas City pollution plumes is evidence that the source regions contain collocated emitters of NO_x and VOCs. This indicates that the refineries and petrochemical plants in the Ship Channel and Texas City areas are the primary sources of the ozone plumes detected downwind of the greater Houston area on September 6th.

4. CONCLUSIONS

The very high ozone concentrations and widespread

ozone exceedances that occurred on August 29th (and the following 2 days) were linked to a combination of two meteorological factors: a) stagnant conditions during the middle of the day allowed a buildup of ozone plumes over and near the source regions and b) aged pollution plumes emitted into the morning offshore flow were recirculated and transported back over the source areas by the afternoon sea breeze thus further increasing the already high ozone concentrations.

During the later part of the pollution episode, when well-defined flow conditions prevailed (September 1st - 6th), the airborne ozone lidar and in situ sensors onboard the NCAR Electra detected ozone plumes downwind of Houston with peak values well above exceedance level. On September 6th, the most striking example of this kind of pollution export, the airborne ozone lidar measured ozone concentrations of more than 130 ppbv up to 150 km downwind of Houston. This suggests that on days with a steady synoptic flow, the Houston ozone plume is exported to the surrounding rural regions, where HRM network coverage is sparse at best. Consequently, the HRM network measurements, concentrated in and near the Houston metropolitan area, indicate relatively clean conditions, while exceedances are, in fact, occurring in the sparsely monitored regions.

ACKNOWLEDGMENT

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REFERENCES

Alvarez II, R. J., C. J. Senff, R. M. Hardesty, D. D. Parrish, W. T. Luke, T. B. Watson, P. H. Daum, and N. Gillani, 1998: Comparisons of airborne lidar measurements of ozone with airborne in situ measurements during the 1995 Southern Oxidants Study. *J. Geophys. Res.*, **103**, 31,155-31,171.

R. M. Banta, C. J. Senff, L. S. Darby, T. B. Ryerson, M. Trainer, and R. J. Alvarez II, 2002: 3-D distribution of ozone during the major pollution event of 30 August 2000 during TEXAQS 2000. Fourth Conference on Atmospheric Chemistry: Urban, Regional, and Global Scale Impacts of Air Pollutants, 13-18 January, 2002, Orlando, FL (Paper 10.17, this volume).

Banta, R. M., C. J. Senff, A. B. White, M. Trainer, R. T. McNider, R. J. Valente, S. D. Mayor, R. J. Alvarez, R. M. Hardesty, D. Parish, and F. C. Fehsenfeld, 1998: Daytime buildup and nighttime transport of urban ozone in the boundary layer during a stagnation episode. *J. Geophys. Res.*, **103**, 22,519-22,544.

Senff, C. J., R. M. Hardesty, R. J. Alvarez II, and S. D. Mayor, 1998: Airborne lidar characterization of power plant plumes during the 1995 Southern Oxidants Study. *J. Geophys. Res.*, **103**, 31,173-31,189.